ARMY RESEARCH LABORATORY

The Response of a Large-Caliber Granular Charge in Confinement to an In-Bed Thermal Initiation

by Lang-Mann Chang

ARL-CR-0648 **June 2010**

prepared by

American Systems Corporation
14151 Park Meadow Drive
Chantilly, VA 20151

under contract

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14. ABSTRACT
Studies have been conducted to experimentally characterize the ignition and early-time combustion processes in a large-caliber propellant charge confined in a closed chamber and initiated by an in-bed hot ignition source. The experiments involve firings of live propellant charges contained in optically clear well-instrumented plastic chambers. There is a perforation through the chamber wall aligned with the ignition source. The studies simulate the circumstance when charge ignition occurs by a hot fragment which has penetrated the chamber wall and has rested inside the propellant bed. Results show that an in-house developed igniter composed of thermite powder (Al-Fe2O3) surrounded by ball powder contained in a cloth tube, initiated by electrical matches, is capable of providing proper ignition stimulus to the propellant charge. A perforation in the chamber wall, created by the penetration of a hot fragment, has a strong effect on the ignition process. Confinement of the charge is also an important factor in accelerating the ignition process. There is a large gradient in pressure and temperature from the ignition site to the chamber ends.

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Contents

List of Figures

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1. Introduction

There are a number of ongoing efforts in the Army and the Navy aimed at meeting insensitive munitions (IM) compliance. One of the efforts is the development of venting technology for metal cartridge cases and metal storage/shipping containers of large-caliber propellant charges. The ultimate goal is to ensure that violent reactions of the propellant charge will not occur when subjected to unplanned stimuli, such as heat, impact, and shock. In this program, both experiments and computer modeling are performed to provide data that help better understand venting mechanisms and develop a methodology of venting technology applicable to various gun propulsion systems.

The present studies are an integral part of the overall effort in support of the development of the venting technology. Experiments were conducted with a charge in a well-defined confinement and initiated by soft ignition (i.e., a static hot ignition source). The experimental setup in the studies was designed to provide essential data for use in the calibration and validation of the subsequent computer modeling, as well as to provide a fundamental understanding of charge ignition dynamics. Similar experimental methodologies have been extensively utilized (*1−4*) and their results have been widely used in support of interior ballistics modeling (*5−7*).

In these studies, a granular propellant charge was contained in an optically clear instrumented plastic chamber. An igniter, developed earlier at the U.S. Army Research Laboratory (ARL) (*8*), was embedded in the charge for propellant initiation. As shown in figure 1, the igniter consists of thermite powder, ball powder, and two electric matches. In the center, thermite (a mixture of 10% $BKNO_3$, 23% Al powder, 3-4.5 microns diameter; and 67% Fe_2O_3 powder, 44 microns diameter), contained in a paper tube, was used to generate numerous hot particles with minimum gas products. This is ideal for simulating the thermal effect of a static hot fragment. Surrounding the paper tube was WC855 ball powder in a cloth tube designed to simulate the fractured propellant grains caused by a hot fragment impact. The ball powder was used because of its regular shape, which can be easily modeled and is available at the laboratory, although the actual fractured grains might appear in various sizes. The thermite and the ball powder weighted 15 and 20 grams, respectively. Both igniter materials were in a well-defined confinement (paper and cloth tubes), intended to be suitable for the interior ballistics modeling. Two electric matches were inserted, equally spaced, into the thermite bed for initiation of the igniter. While the lower end of the cloth tube was sealed, the upper end was taped tightly around the electric match lead wires. The overall size of the igniter is 10 cm (4 inches) in length and 2.22 cm (0.875 inch) in diameter, which properly fit into the present charge. This igniter is structurally similar to the one used in Birk et al. (*4*).

High-speed cameras, pressure transducers, and thermocouples were employed for recording the ignition and early-time combustion events. Data obtained include the flame propagation, pressure rise, and temperature rise at several locations in the propellant charge.

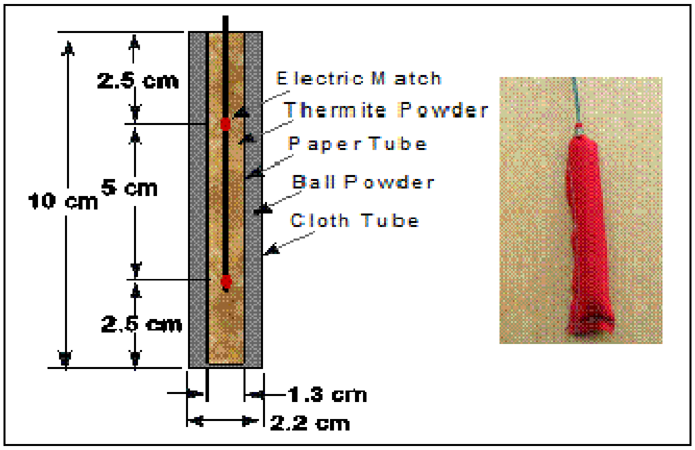

Figure 1. Igniter (used with permission from reference 8).

2. Experimental Setup

The experiments were carried out with firings of live propellant charge contained in an optically clear plastic chamber, which allowed direct visualization of flame propagation. This propellant-filled chamber is called "ballistic simulator" hereafter. Two chamber lengths, 15 cm (6 inches) and 76 cm (30 inches), were adopted for two separate test firings. Both chambers had the same inside diameter of 16.5 cm (6.5 inches) and wall thickness of 1.3 cm (0.5 inch), capable of withstanding pressures higher than 13.8 megapascal (MPa) (2000 psi) before rupture. By the time of chamber rupture, the flame front would have nearly reached the far ends of the chamber.

Figure 2 shows the simulator chambers prior to the propellant was filled. The long (76-cm) chamber was comparable, in the size, to a typical large-caliber cartridge case. There was an open hole of 1.3 cm (0.5 inch) diameter through the chamber wall at the midsection, representing a perforation created by the penetration of a hot fragment. The short chamber contained 2.12 Kg (4.66 lbs), comparing to 14.8 Kg (32.47 lbs) in the long chamber, giving significant savings of propellant consumption and assembling time. It was used for checking out firing operations, recording systems, and instrumentation. Additionally, because of relatively simple configuration, the setup is valuable for validation of preliminary exercises of the interior ballistics modeling.

In the 15-cm charge simulator, the chamber was fully filled (not vibrated) with M30A2 propellant grains without apparent ullage. The igniter was carefully placed at the midsection of the propellant bed. The two chamber ends were closed with two heavy steel plates, fastened by four 2.54-cm steel rods. O-rings were used to seal the chamber ends. A Kistler pressure gage

(Model 211B2) together with a thermocouple (OMEGA K-type, 0.00508-cm (0.002-inch) diameter) was installed in each end plate.

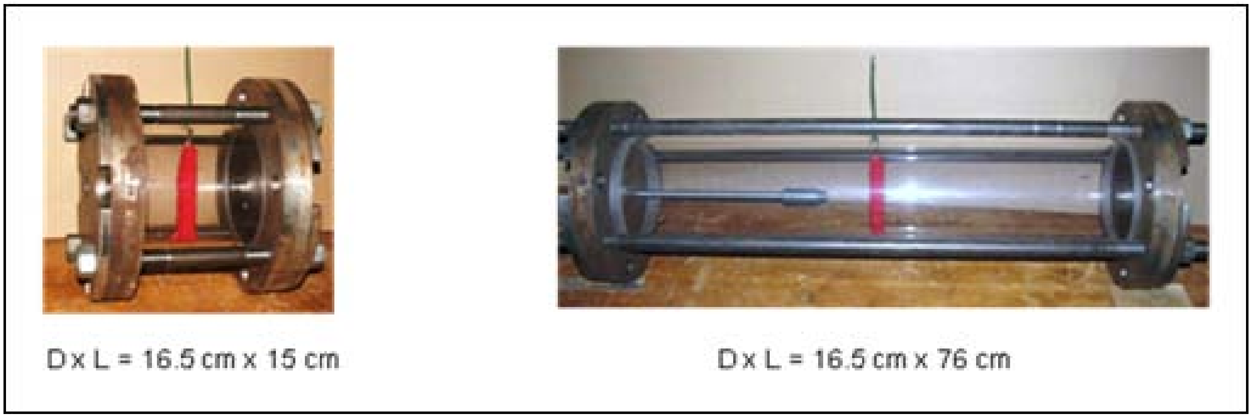

Figure 2. Empty simulator chambers.

In the 76-cm charge simulator, an additional pressure gage together with a thermocouple was placed near the igniter inside the propellant bed, as seen in figure 3. This allowed monitoring the early-time pressure and temperature rises following the initiation of the igniter. There were another two thermocouples mounted near the inner surface of the chamber wall on each side of the igniter. A “bump” was glued to the chamber wall on the upstream side to prevent the thermocouple from being swept away by moving propellant grains during the ignition/combustion processes. Figure 3 also shows a front view and a top view of the charge before firing. The two white spots on the top view were the connectors for thermocouple wires.

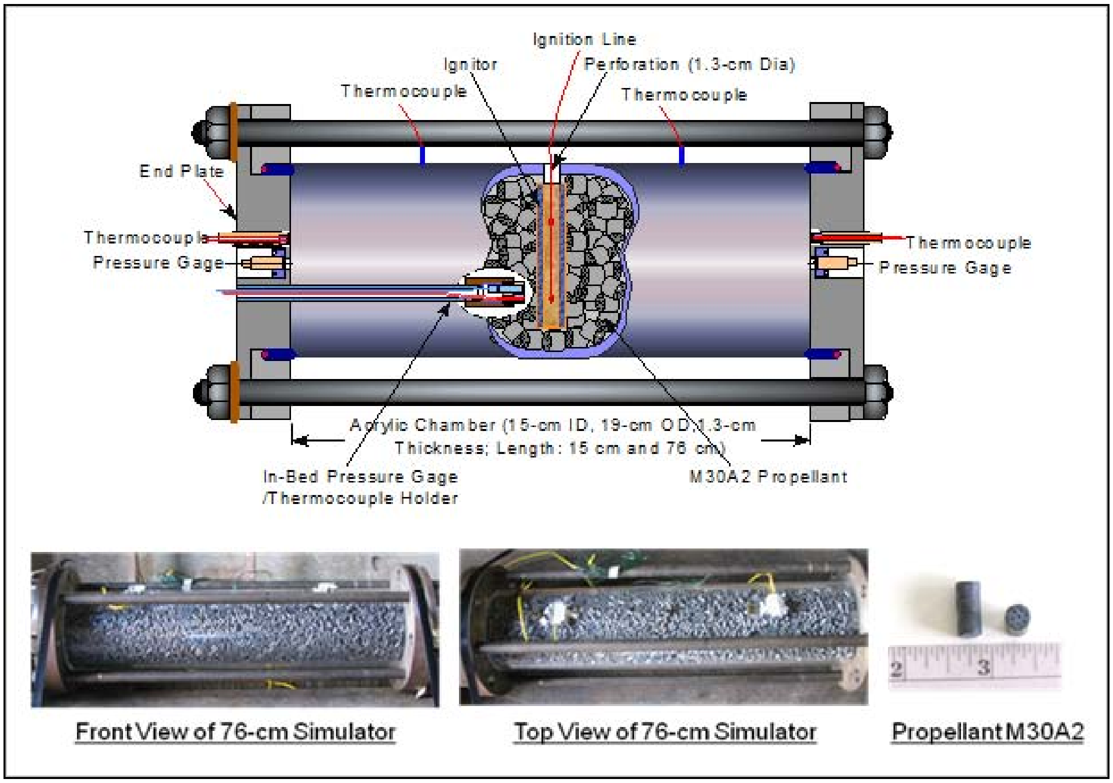

Figure 3. Charge simulator.

In filming the flame propagation, two Phantom V7 high-speed digital cameras were employed. Their framing rates were set at 4,000 and 7,000 frames/second, respectively. The higher framing rate would provide more details of the flamespreading process, which could be helpful in investigating some important transitions of the ignition events. A camera setting of 10 μs exposure time and f/2.8 aperture was found appropriate, producing clear images of the flamespreading along the propellant bed.

3. Results and Discussion

Both the 15-cm and the 76-cm charge systems were fired at an ambient temperature of approximately 25 °C.

Figure 4 displays a series of images reprinted from the high-speed video showing the flamespreading initiated from the igniter located at the midsection of the propellant charge. It is noted that the time indicated on the images are the time counted from the instant that the first visible light appears. The first visible light appeared right under the vent hole on the top of the chamber, where the camera view was less obscured by propellant. The exact time at which the firing voltage was applied was not determined due to a difficulty occurring in the video recording system. The images evidence that venting occurred at a very early time—immediately following the functioning of the igniter. The result also indicated that intense flame first developed near the vent hole area. This apparently resulted from a strong convective heat transfer effect of the outgoing hot gas flow from the propellant bed, i.e., the hot gas flow induced vigorous propellant ignition along its pathway. The flame then spread almost instantly to the chamber ends and rapidly to the far side of the vent hole. The high intensity light made it difficult to determine the instant that the propellant started igniting and at what time the chamber started rupturing.

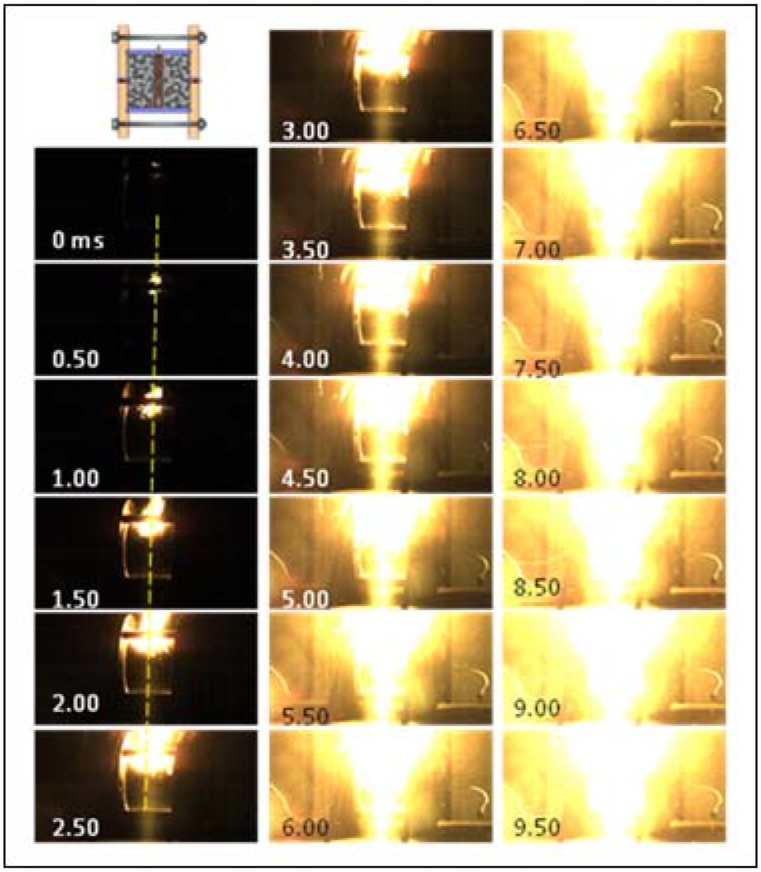

Figure 4. Flamespreading in the 15-cm simulator.

Figure 5 presents the pressure-time (p-t) trace recorded at one of the two chamber ends, while the data at the other chamber end were lost. Note that the time along the time axis in the plot was measured from the instant that the firing voltage was applied. The early portion of the pressure-time trace, which should start from 0 psi, was lost during the data acquisition process. Nevertheless, the curve shows a significant pressure rise occurred shortly after 20 ms. This transition apparently reveals that the propellant ignition had started. Following this, the pressure increased very rapidly until the chamber rupture occurred at 26.2 ms at which the pressure reached 26.3 MPa (3,817 psi). In the figure, the temperature-time trace at the chamber end, initiated at the ambient temperature of 25 °C, shows that the temperature in the region continued rising to about 320 °C (608 °F) for a period of time after the occurrence of chamber rupture.

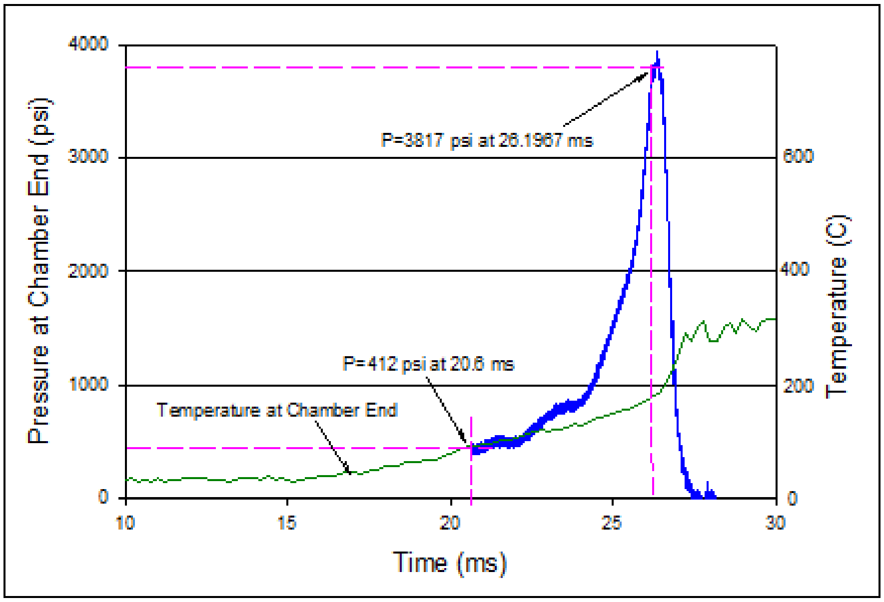

Figure 5. Pressure-time and temperature-time traces at the chamber end of the 15-cm simulator.

For the 76-cm long propellant charge, figure 6 reveals details of the flame development/spread from the igniter. The igniter started functioning at about 11 ms or earlier after application of the firing voltage. Like that observed in the firing with the 15-cm simulator, venting occurred very early. However, unlike the previous firing, the flame was confined in the near region around the igniter for a quite long time—until about 45 ms. During this period, the venting continuously increased and then decreased (determined by the increasing and the decreasing of light intensity in the venting). The transition occurred at about 42.5 ms. After that, the increasing venting and flamespreading clearly reveal that propellant ignition had commenced. Along with the rapid flamespreading toward the chamber ends, the pressure rise had eventually exceeded the strength of the chamber wall and caused it to rupture immediately after 56 ms had elapsed. Prior to the chamber rupture, the flame propagated in a nearly one-dimensional pattern as it approached the chamber ends.

Figure 7 shows the pressure-time (p-t) traces at three locations as indicated. Despite some wavy behavior occurring at the early time due to electronic noises, P3 (near the igniter) rose quickly at about 42.5 ms and then very sharply after the time of 50 ms. The pressure rise eventually reached about 32.4 MPa (4700 psi) before falling back to 0 psi upon the rupture of the chamber. The pressure rises, P1 and P2, at the chamber ends were significantly behind P3, show a large pressure gradient from the midsection to the far ends of the chamber.

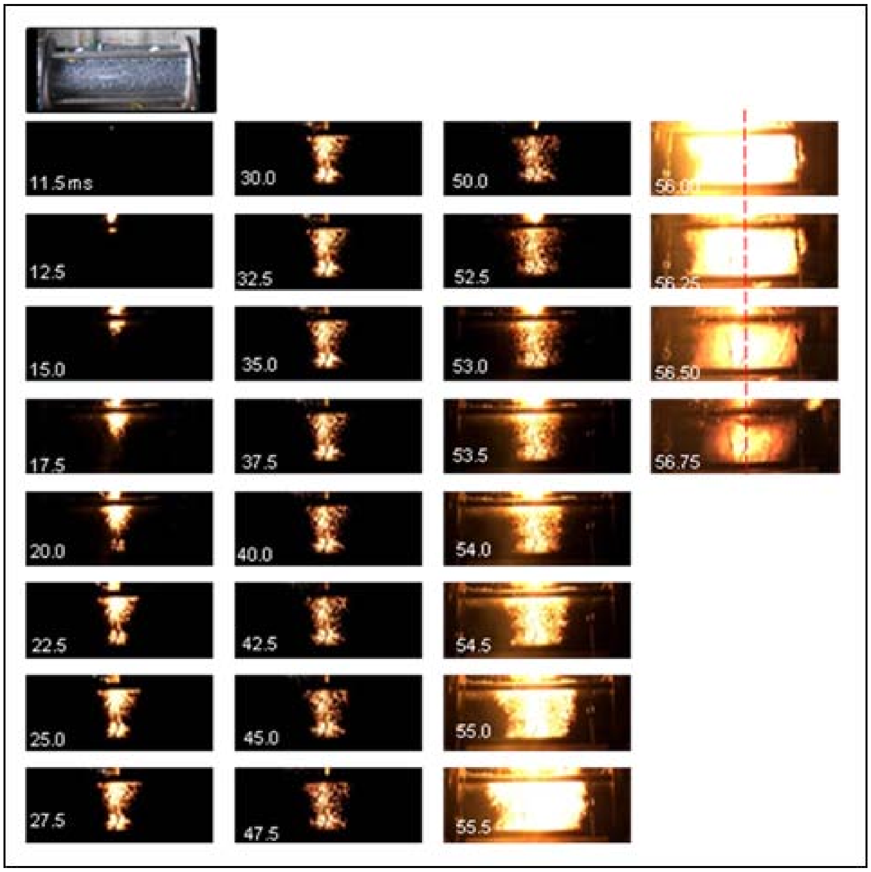

Figure 6. Flamespreading in the 76-cm simulator.

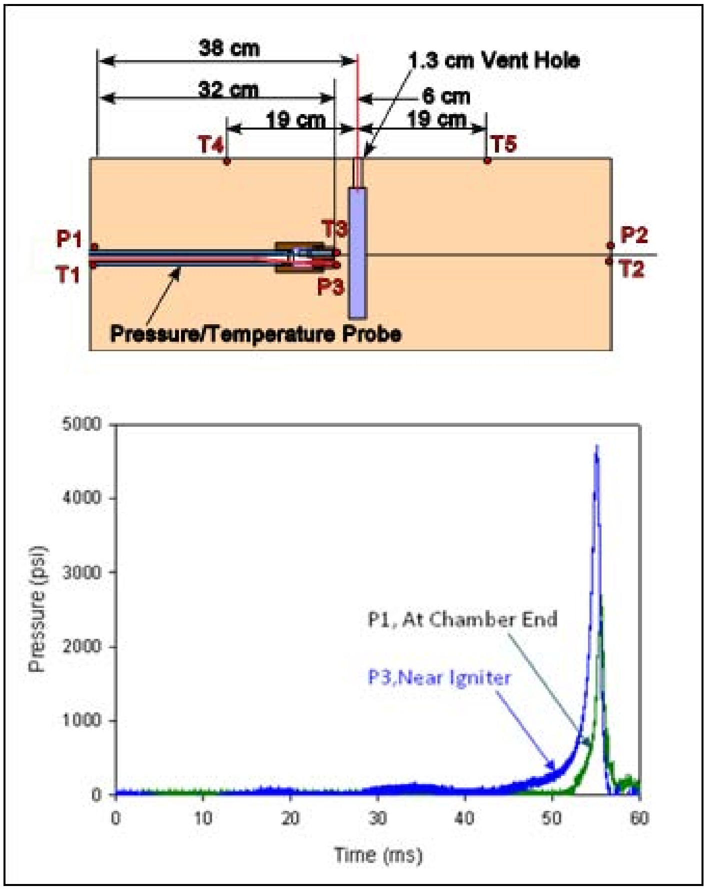

Figure 7. Pressure-time in the 76-cm simulator.

The gas temperature in the chamber shown in figure 8, T3 (near the igniter), started increasing at 15 ms. The fast temperature rise indicated a fast heat energy release from the igniter. The slope of the temperature curve decreased after 20 ms, indicating that the igniter output had passed its peak. It then began to rise rapidly after passing 40 ms, apparently resulting from propellant ignition. The transitions of the temperature curve T3 correlate very well with the image evidences (see figure 6) and pressure data (see figure 9). There is a large gradient in temperature from T3 to T1, located at the chamber end, partly due to the cold air stagnated locally in the region.

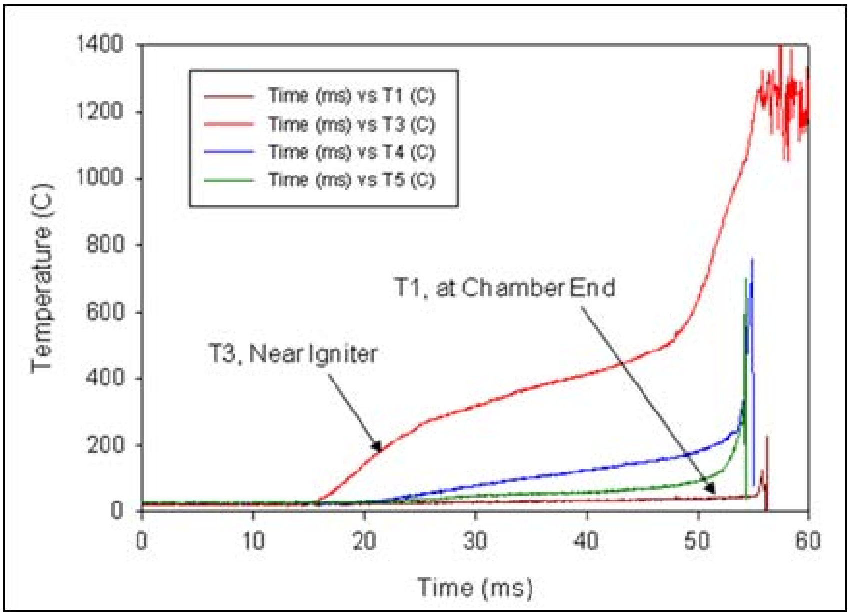

Figure 8. Temperature-time traces in the 76-cm simulator.

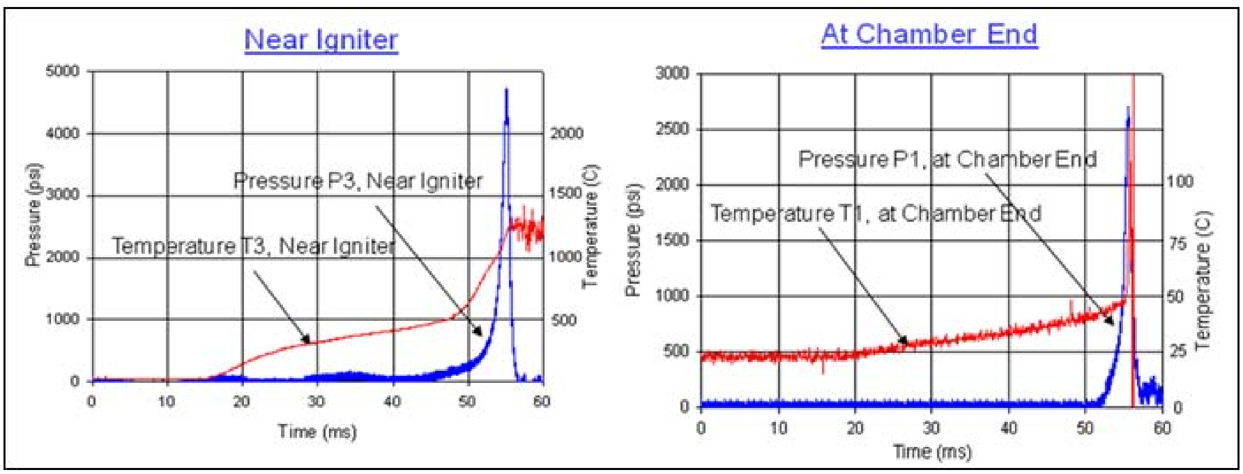

Figure 9. Pressure-time and temperature-time in the 76-cm simulator.

4. Summary

The response of a large-caliber granular charge in confinement to an in-bed thermal initiation has been characterized and analyzed. The results show that:

- Venting from the perforation occurred very early, immediately following the functioning of the igniter.
- Flamespread initiated in the region near the perforation, and it was fairly symmetric toward the chamber ends. As it approached the chamber ends, the flamespread was nearly one-dimensional.
- Chamber rupture initiated in the perforation area (near the midsection of the chamber in the present experimental setup). Together with the preceding item, this shows that the perforation played an important role in flamespreading and chamber rupturing.
- Propellant ignition occurred much earlier in the 15-cm chamber than in the 76-cm chamber (approximately 15 ms vs. approximately 42.5 ms after application of the firing voltage), demonstrating a strong effect of confinement (smaller volume in the 15-cm chamber resulting in a higher pressurization rate which, in turn, resulting in a higher local pressure and thus a higher burning rate of propellant).
- There was a large gradient in pressure and temperature from the ignition site to the chamber ends due to localized ignition in the midsection of the propellant bed.

For immediate use, the results have provided the essential data needed for calibration and validation of the upcoming interior ballistics modeling which will be performed at ARL.

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